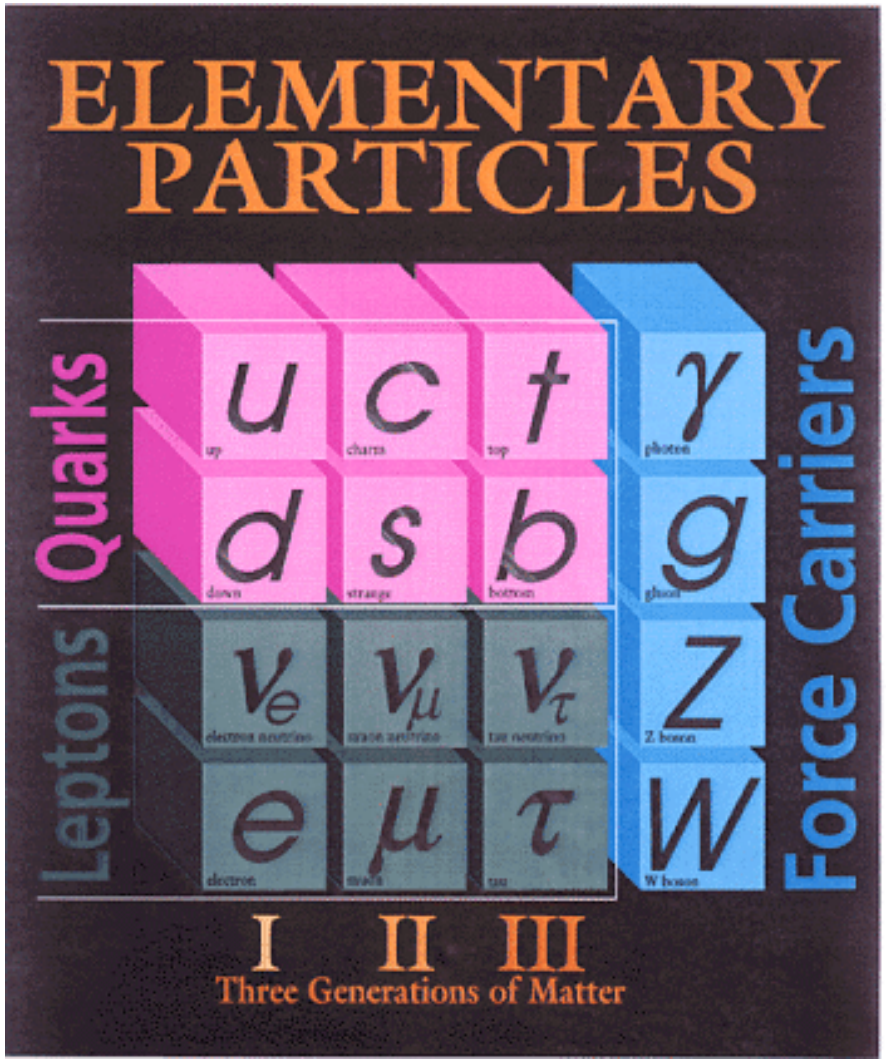
STAR Experiment at RHIC

Nu Xu (for STAR Collaboration)

Nuclear Science Division
Lawrence Berkeley National Laboratory

Many Thanks to the Organizers!

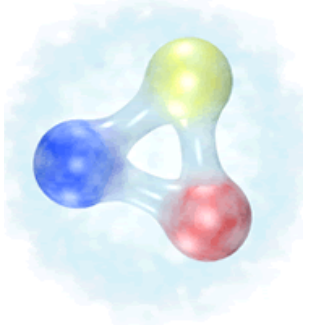
Quantum Chromodynamics



1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.
2) Gluons hold quarks together to from hadrons:

meson

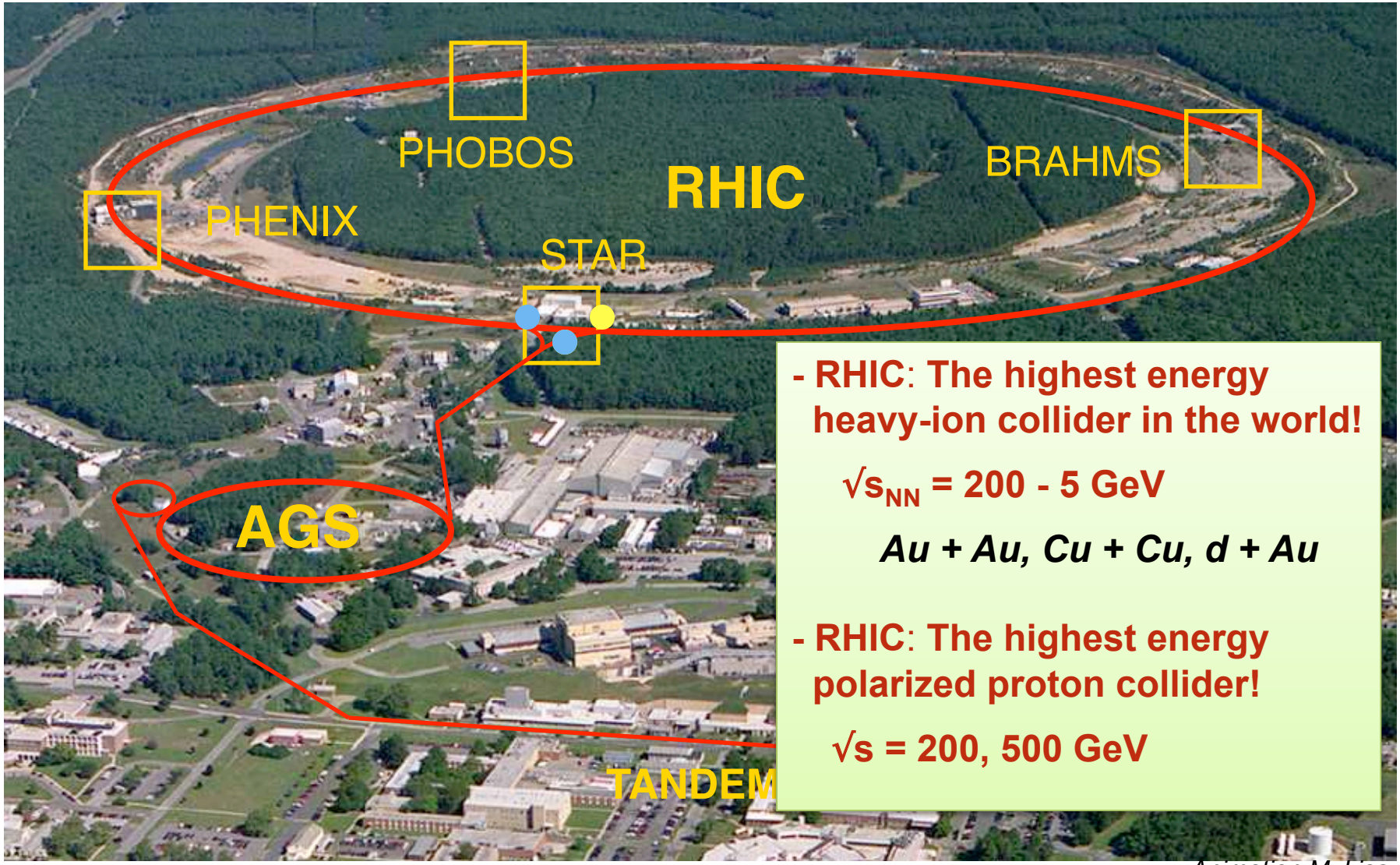
baryon



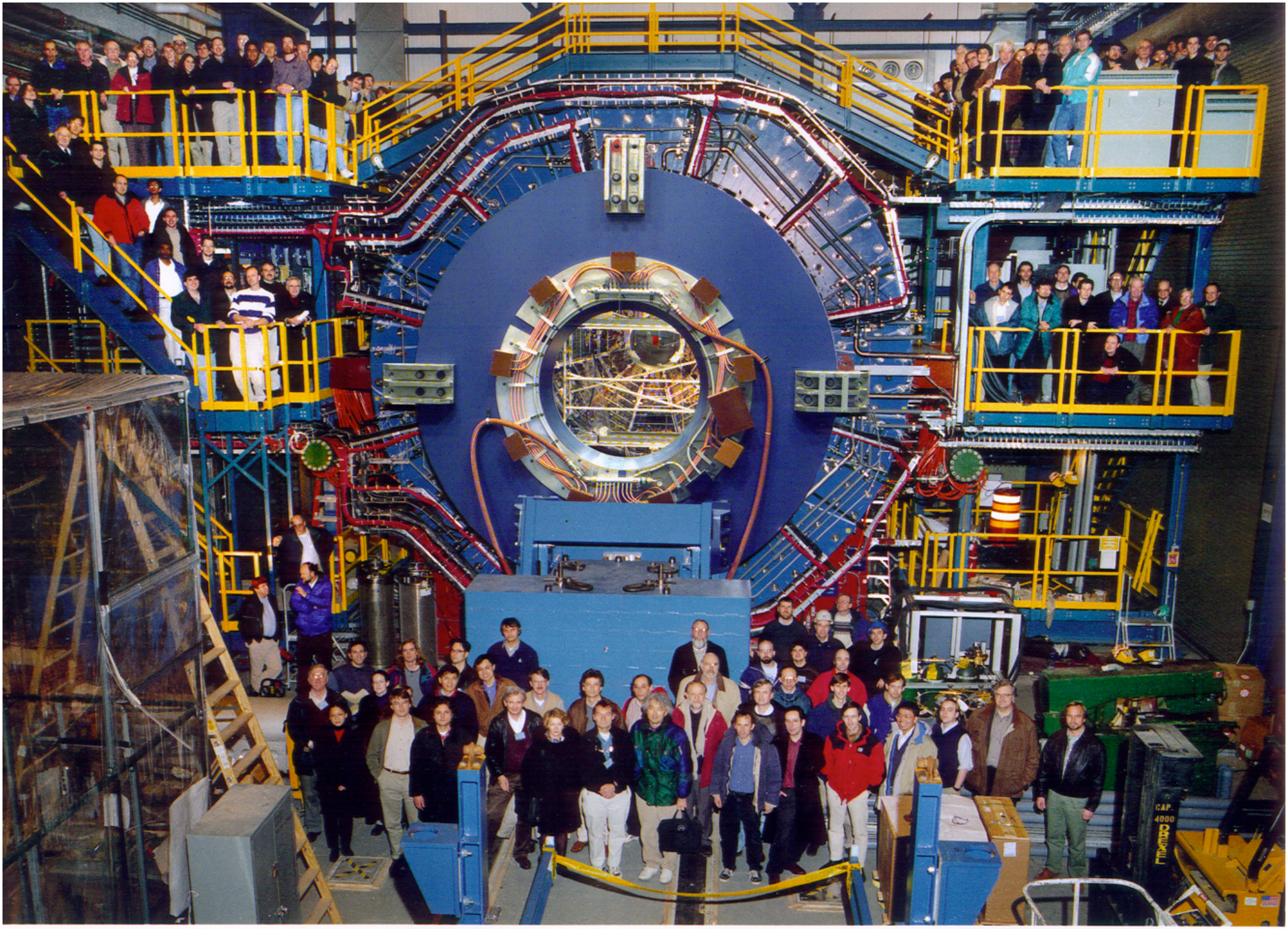
3) Gluons and quarks, or partons, typically exist in a color singlet state: ***confinement.***

Relativistic Heavy Ion Collider (RHIC)

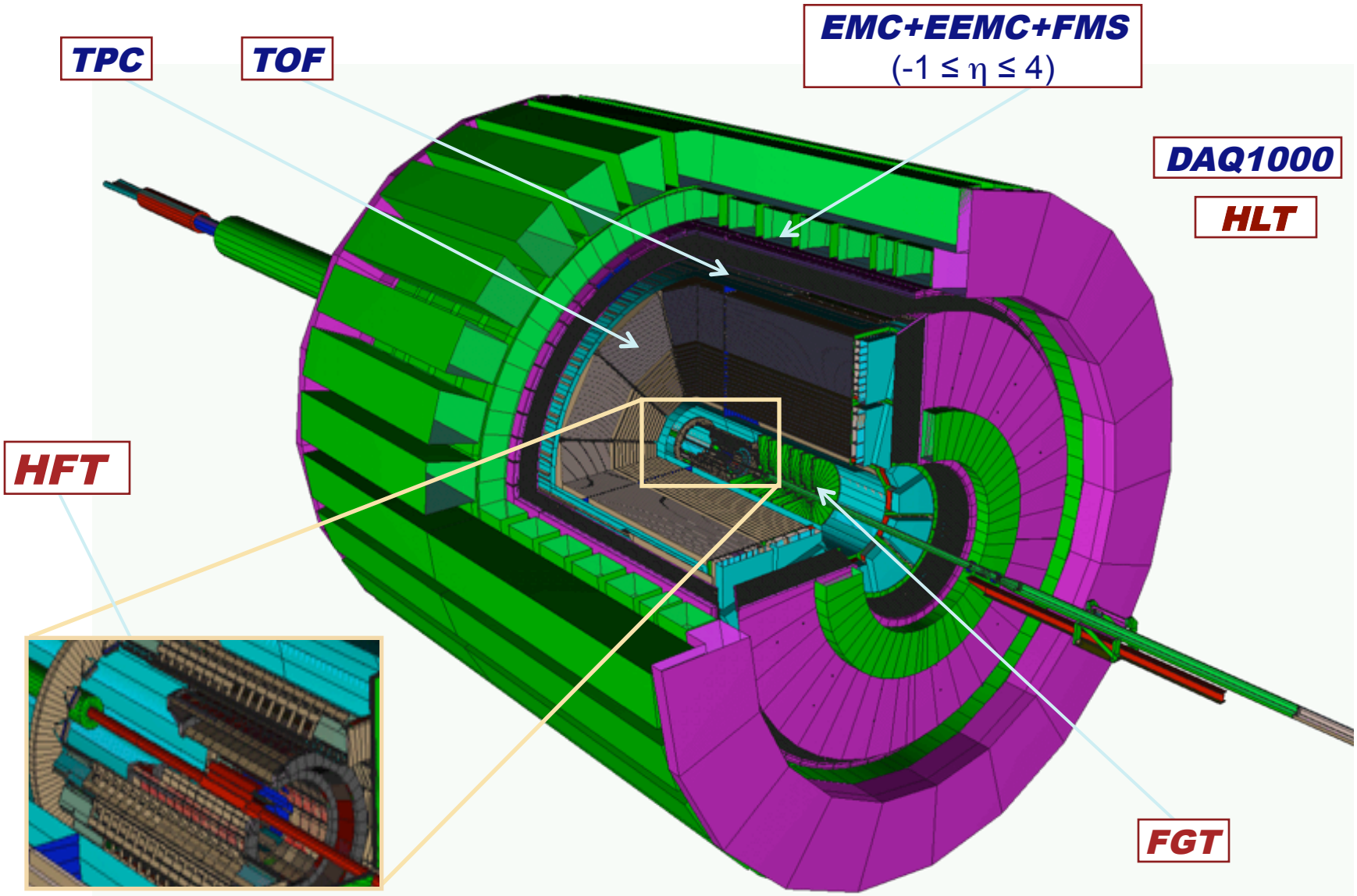
Brookhaven National Laboratory (BNL), Upton, NY



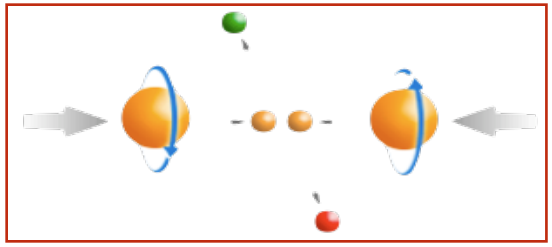
Animation M. Lisa


CAP.
4000
Caterpillar

STAR Detectors: *Full 2π particle identification!*

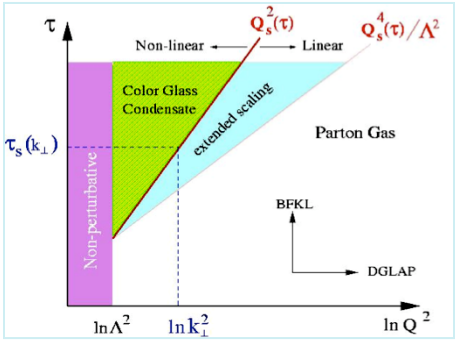


STAR Physics Focus



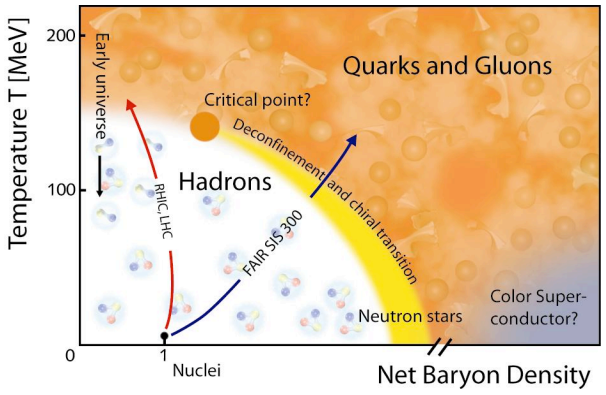
Polarized *p+p* program

- Study ***proton intrinsic properties***



Forward program

- Study low-x properties, search for ***CGC***
- Study elastic (inelastic) processes (pp2pp)
- Investigate ***gluonic exchanges***



1) At 200 GeV top energy

- Study ***medium properties, EoS***
- pQCD in hot and dense medium

2) RHIC beam energy scan

- Search for the ***QCD critical point***
- Chiral symmetry restoration

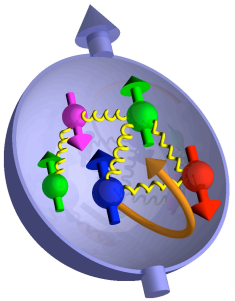
Outline

1) Results from spin program

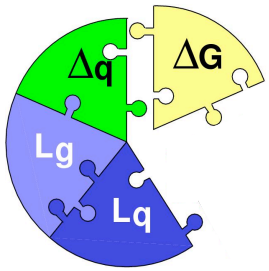
2) Results from heavy-ion program

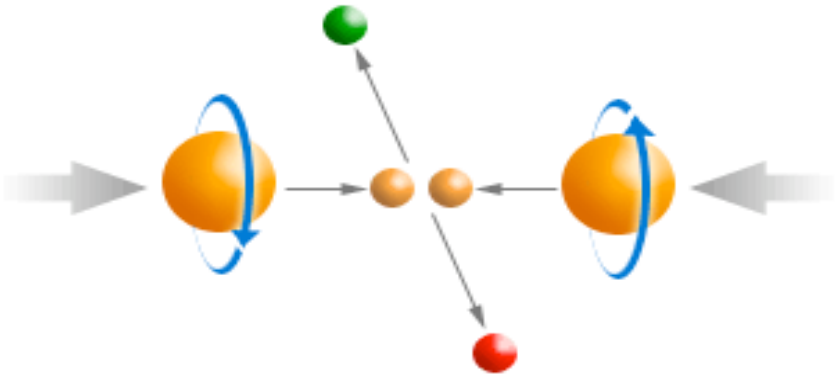
3) Future programs

More interesting results can be found at
http://www.star.bnl.gov/



Proton Spin Physics

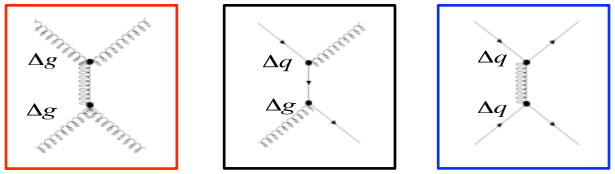




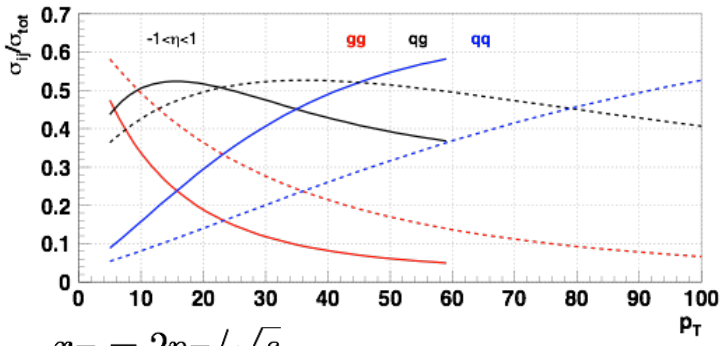
Study proton spin structure with QCD degrees of freedom: quarks and gluons

Δg Measurements at RHIC

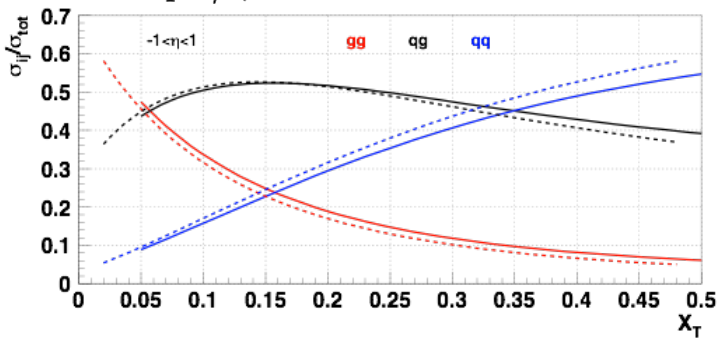
Partonic Processes

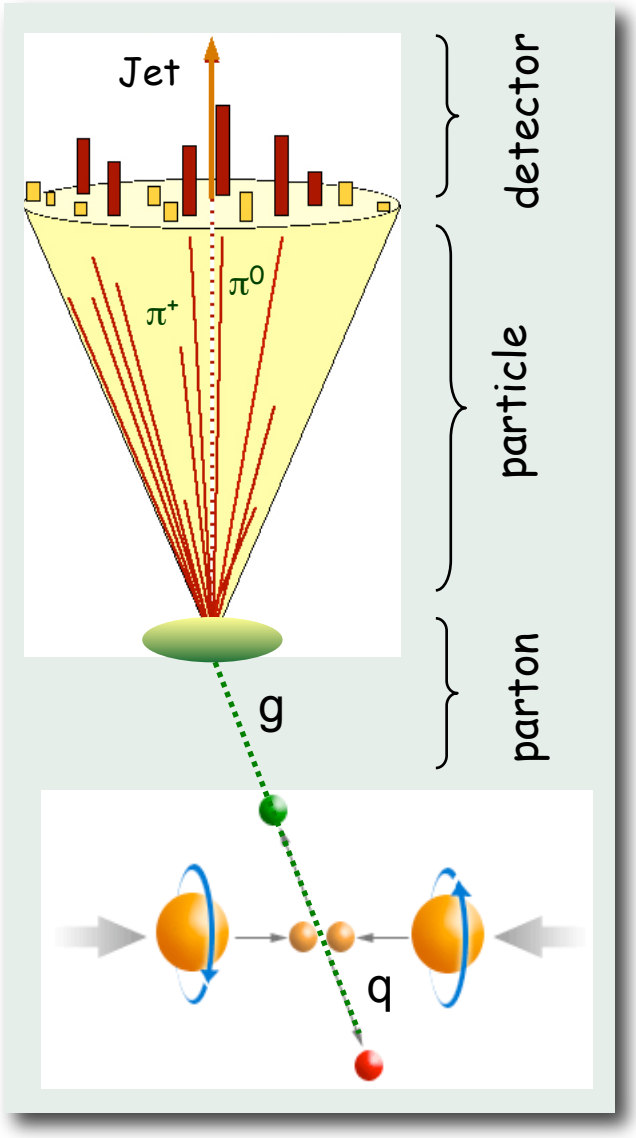


Inclusive Jet production (200GeV: Solid line / 500GeV: Dashed line)

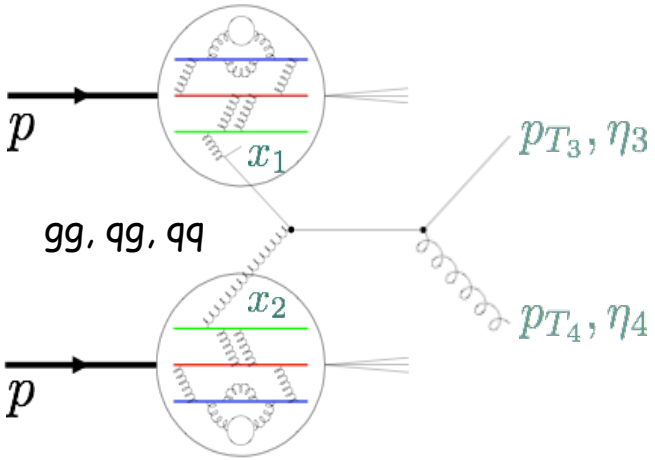


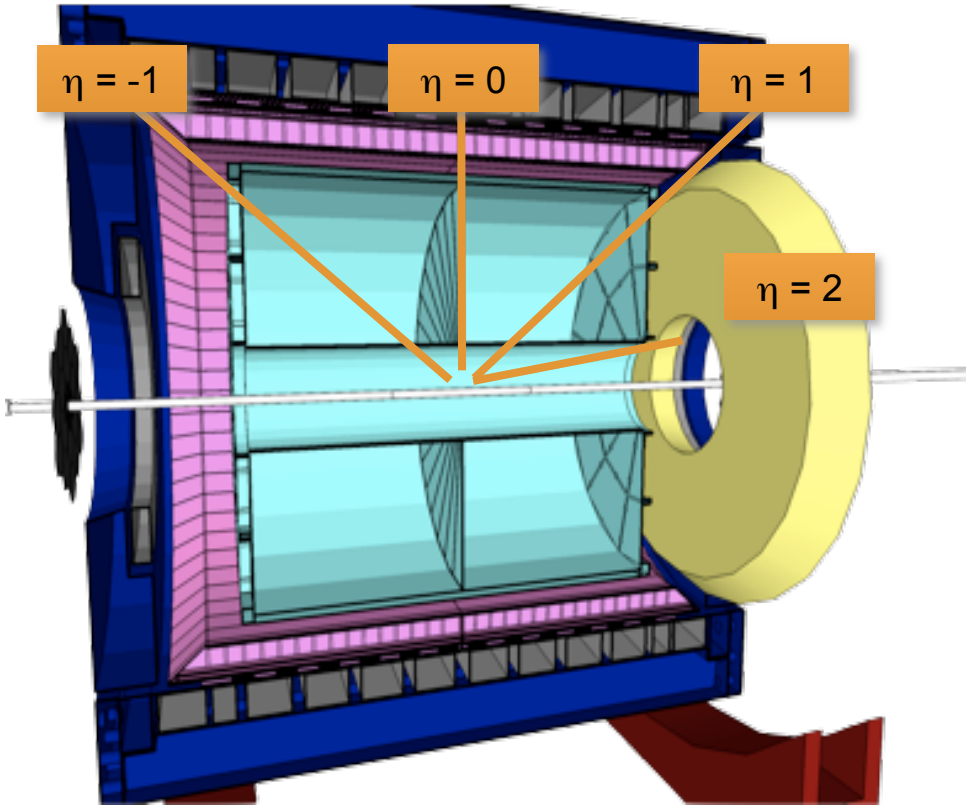
$x_T = 2p_T/\sqrt{s}$





Polarized *p*+*p* Measurements at STAR





STAR: Large acceptance for correlation measurements

di-jets/hadron and γ-jet

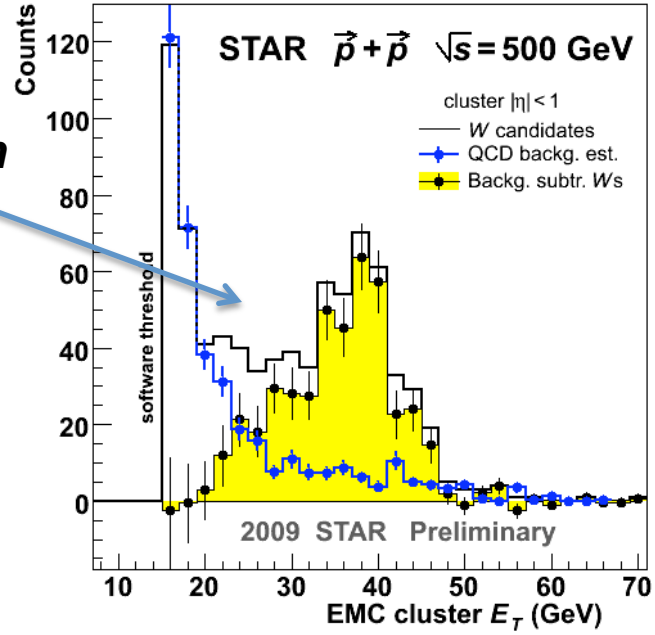
$$x_{1(2)} = \frac{1}{\sqrt{s}}\left[p_{T_3} e^{\eta_3(-\eta_3)} + p_{T_4} e^{\eta_4(-\eta_4)}\right]$$

$$M = \sqrt{x_1 x_2 s} \qquad \eta_3 + \eta_4 = \ln\frac{x_1}{x_2} \qquad \cos\theta^* = \tanh\left(\frac{\eta_3 - \eta_4}{2}\right)$$

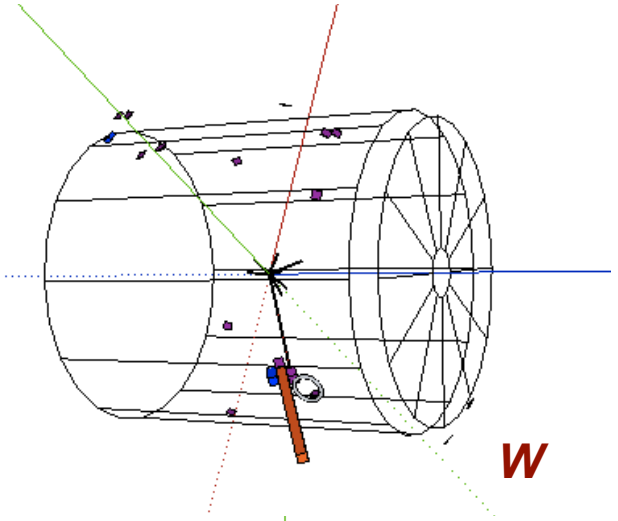
500 GeV p+p Collisions

W

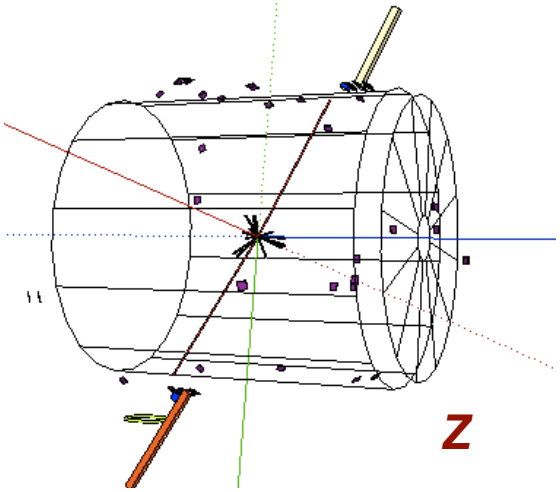
jacobian



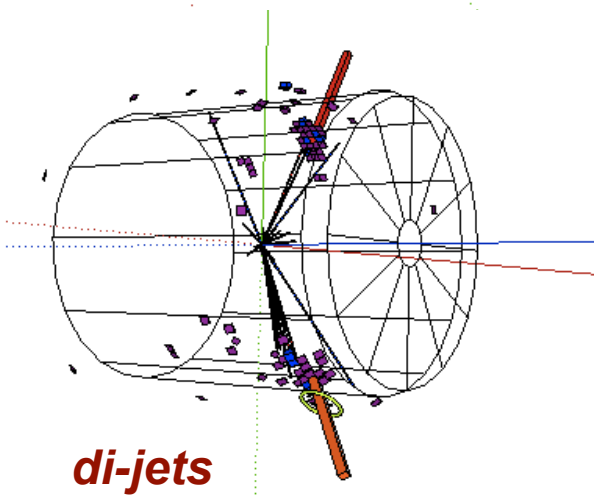
STAR Preliminary



W

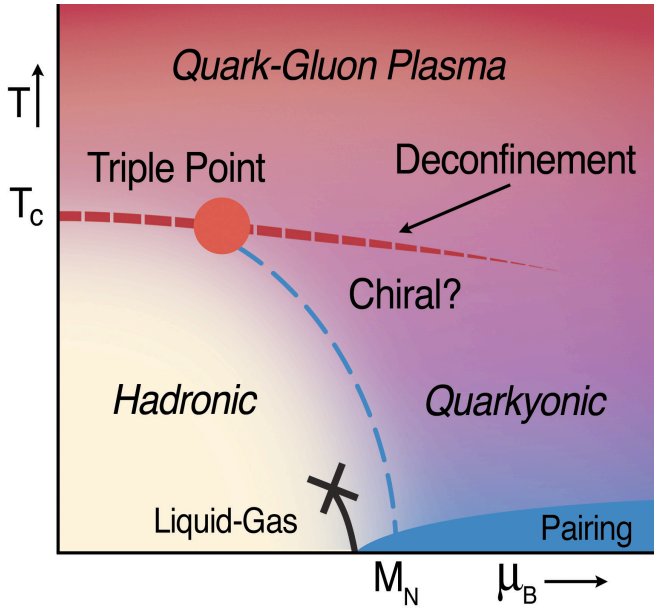


Z



di-jets

High-Energy Nuclear Collisions



Study QCD phase structure and search for the QCD Critical point

sQGP and the QCD Phase Diagram

In 200 GeV Au+Au collisions at RHIC, strongly interacting matter formed:

- **Jet energy loss: R_{AA}**
- **Strong collectivity: v_0, v_1, v_2**
- **Hadronization via coalescence: n_q-scaling**

Questions:

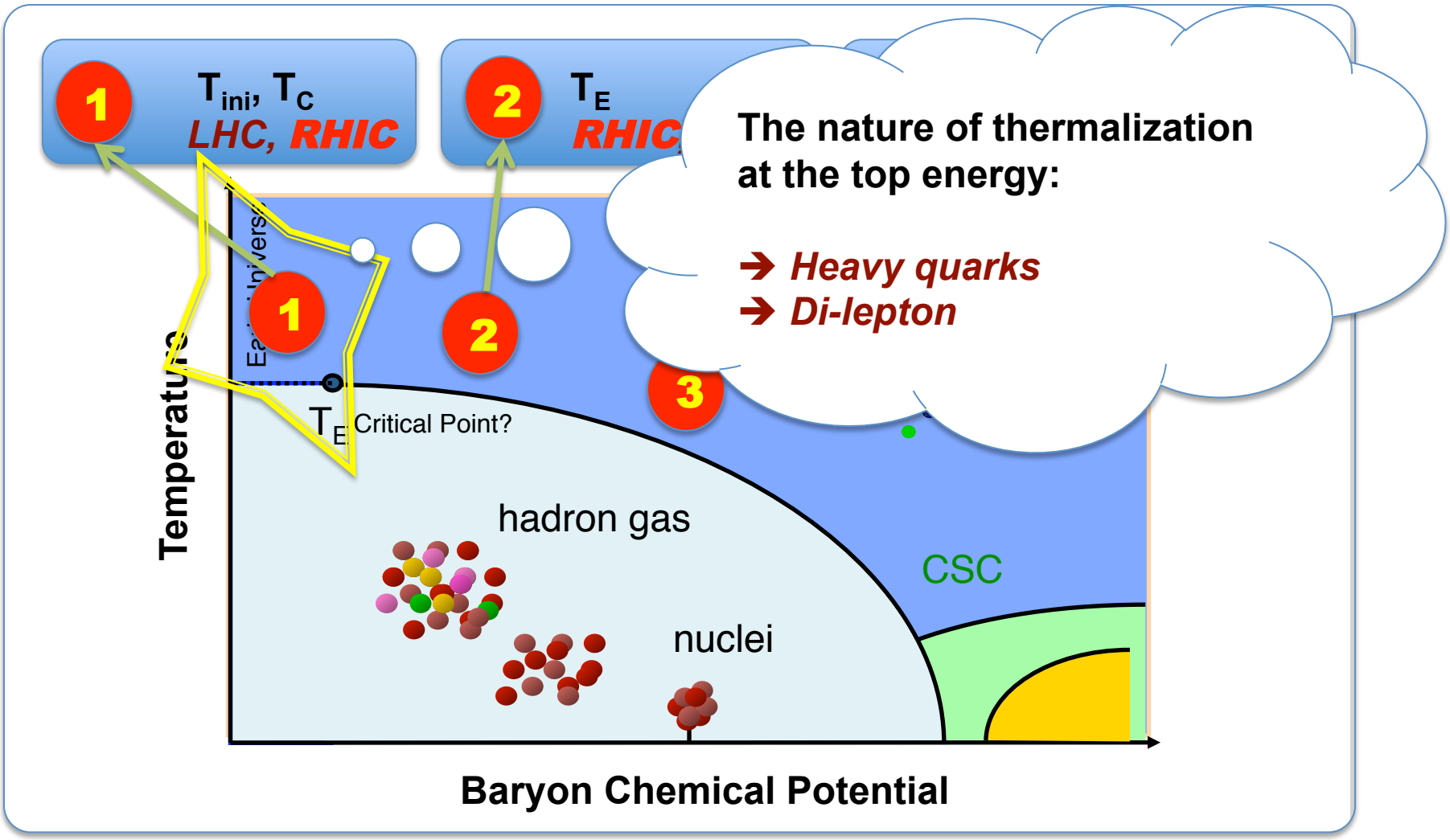
Is thermalization reached at RHIC?

- **Systematic analysis with dN/dp_T and dv_2/dp_T results…**
- ***Heavy quark and di-lepton measurements***

When (at which energy) does this transition happen?
What does the QCD phase diagram look like?

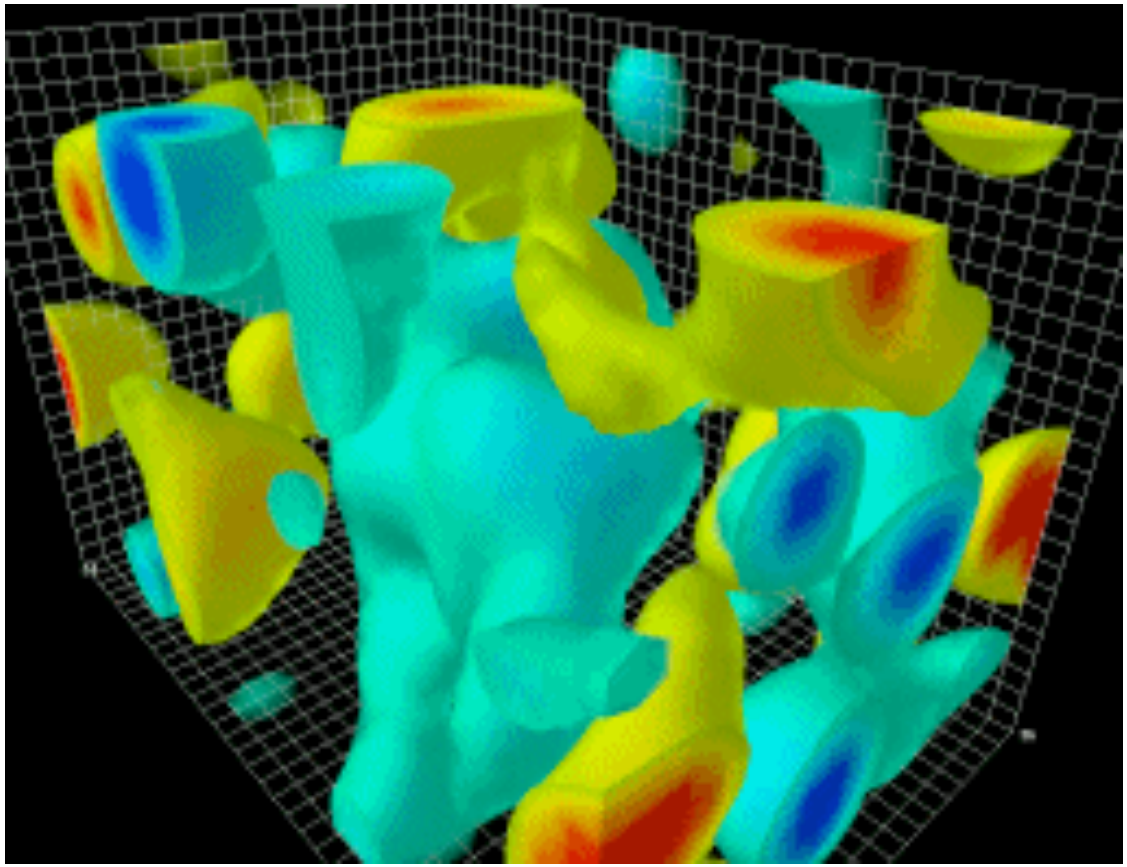
- ***RHIC beam energy scan*** **(BES)**

The QCD Phase Diagram and High-Energy Nuclear Collisions



Search for Local Parity Violation

in High Energy Nuclear Collisions



Animation by *Derek Leinweber*

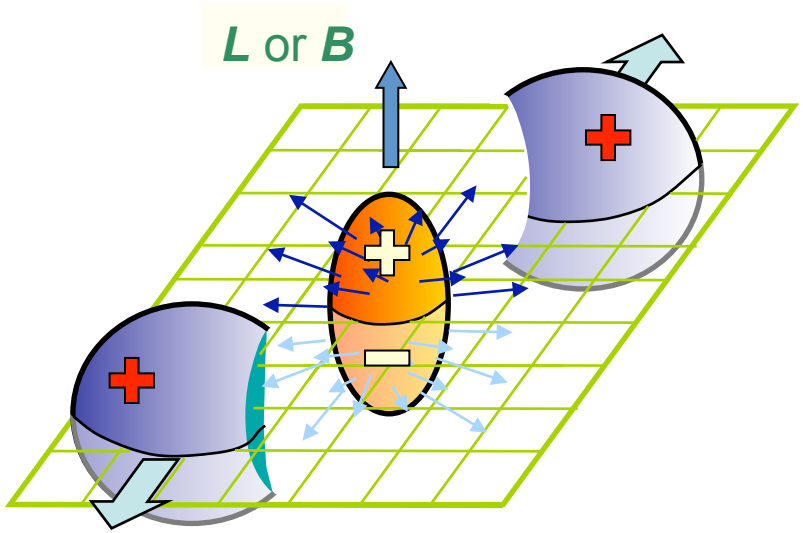
Topological transitions have never been observed *directly* (e.g. at the level of quarks in DIS). An observation of the *spontaneous* ***strong***, ***local*** **parity violation** would be a clear proof for the existence of the physics.

Chiral Magnetic Effect:

Kharzeev, PL ***B633*** 260 (06).
Kharzeev, *et al,* NP ***A797*** 67(07).
Kharzeev, *et al,* NP ***A803*** 227(08).
Fukushima, *et al,* PR***D78***, 074033(08).

Search for Local Parity Violation

in High Energy Nuclear Collisions

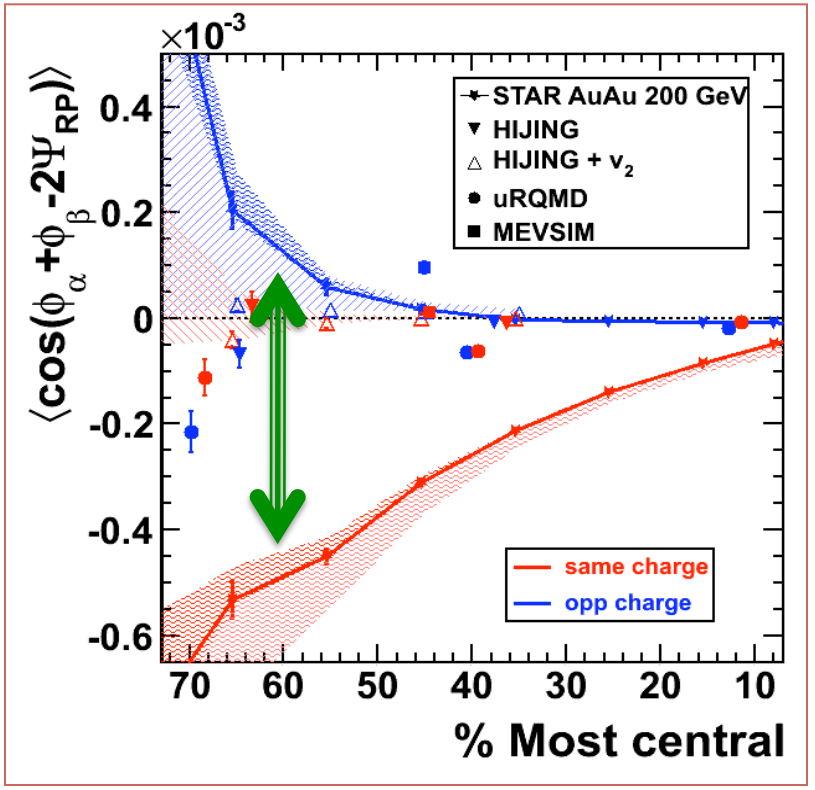


$$\left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_{RP}\right)\right\rangle$$

Parity even observable

Voloshin, PR C62, 044901(00).

STAR; arXiv: 0909.1739 (PRL); 0909.1717 (PRC).

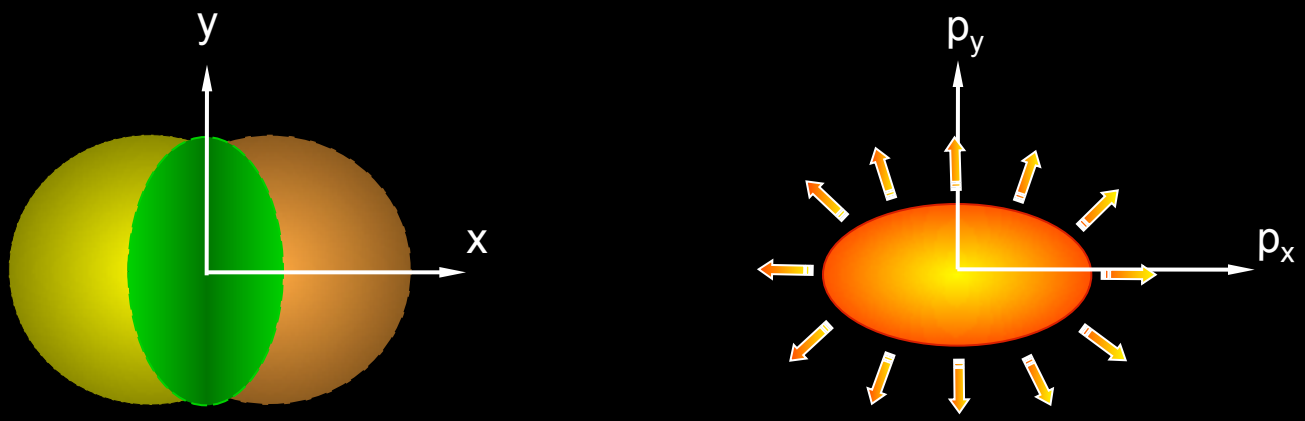


The separation between the same-charge and opposite-charge correlations.

- **Strong external EM field**
- ***De-confinement* and *Chiral symmetry restoration***

Anisotropy Parameter v_2

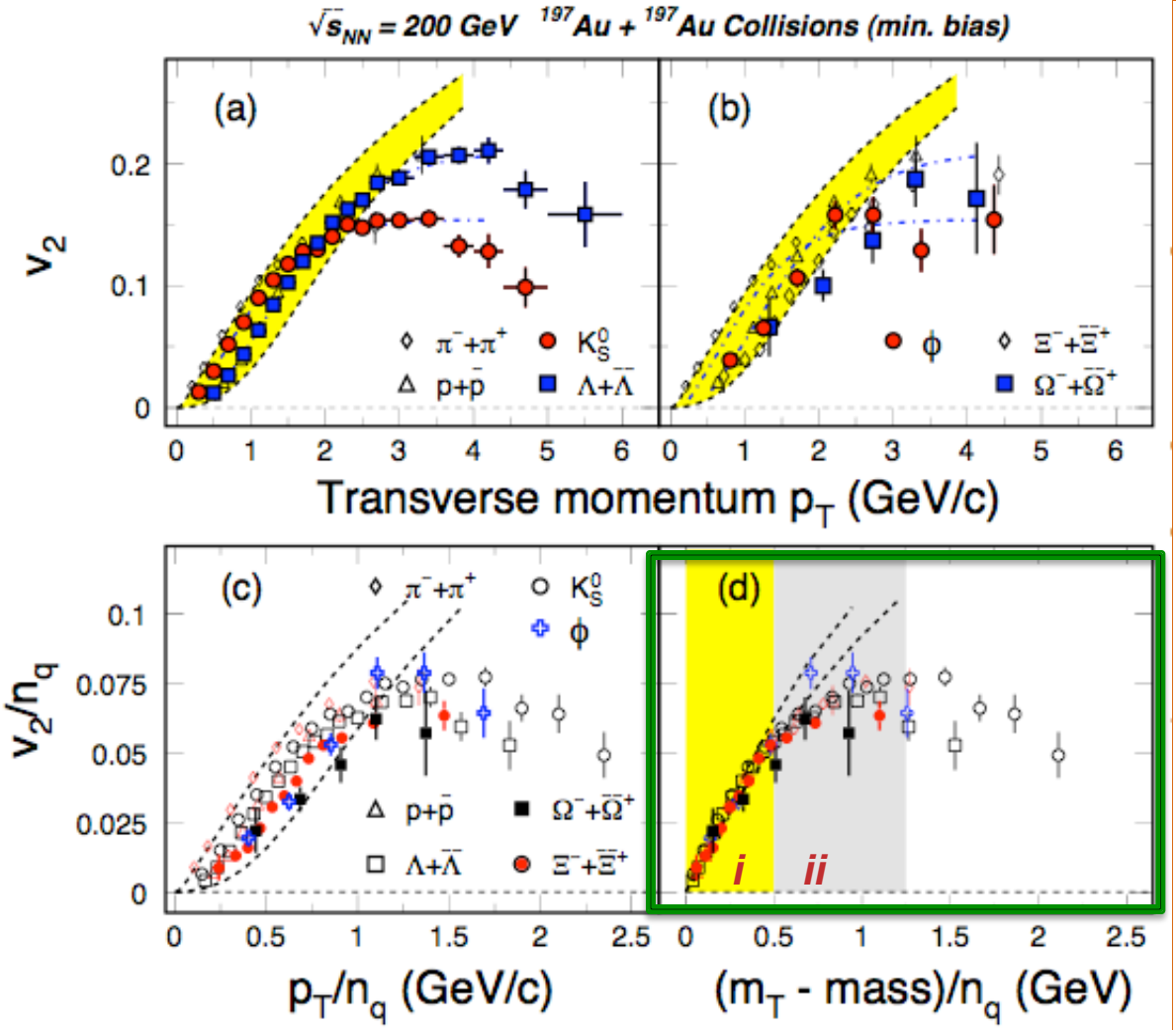
coordinate-space-anisotropy ⇨ momentum-space-anisotropy



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

Collectivity, Deconfinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

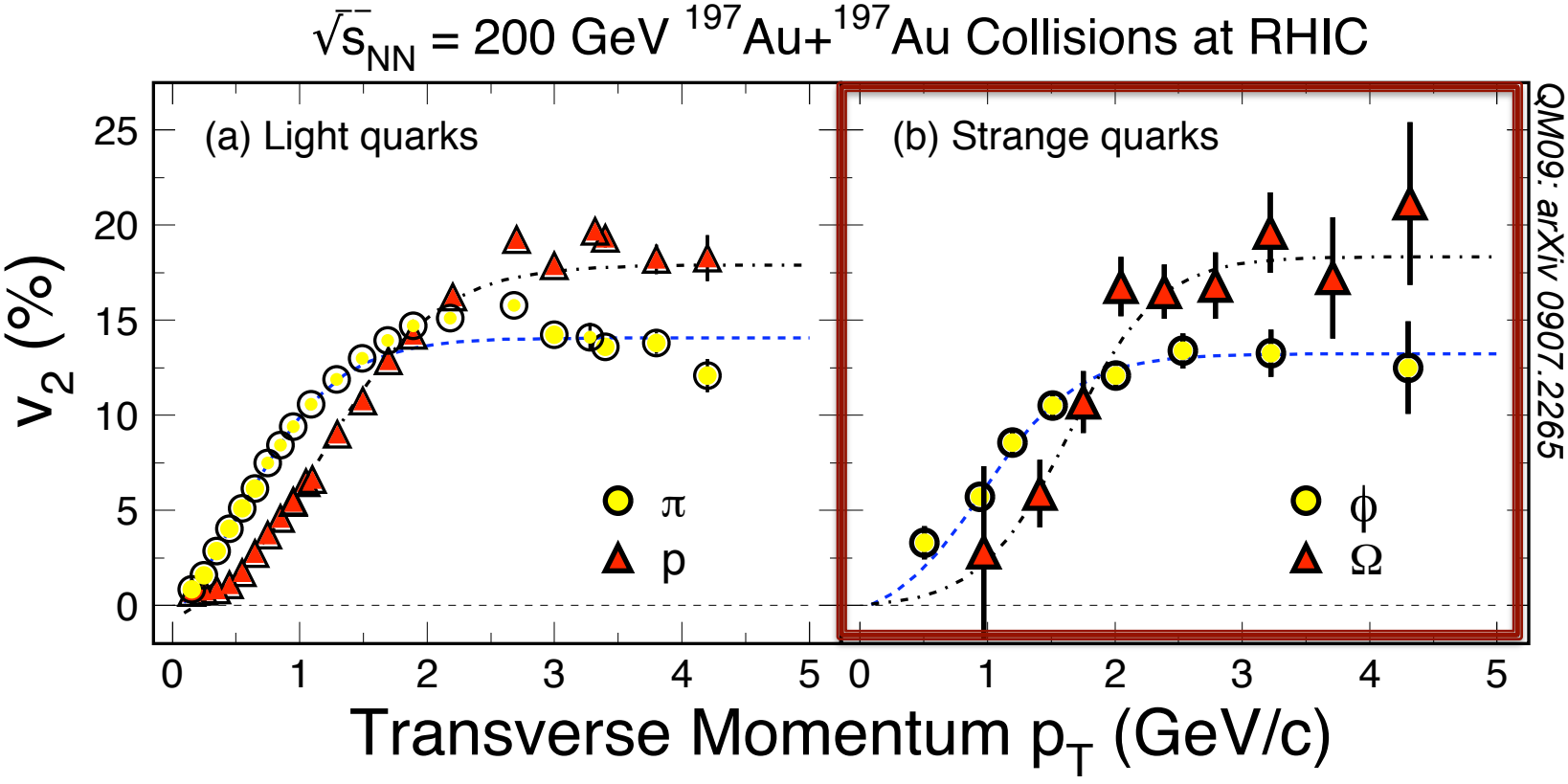
➪ **N_q scaling**
novel hadronization process

➪ **Parton flow**
De-confinement

*PHENIX: PRL **91**, 182301(03)*
*STAR: PRL **92**, 052302(04), **95**, 122301(05)*
nucl-ex/0405022, QM05

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

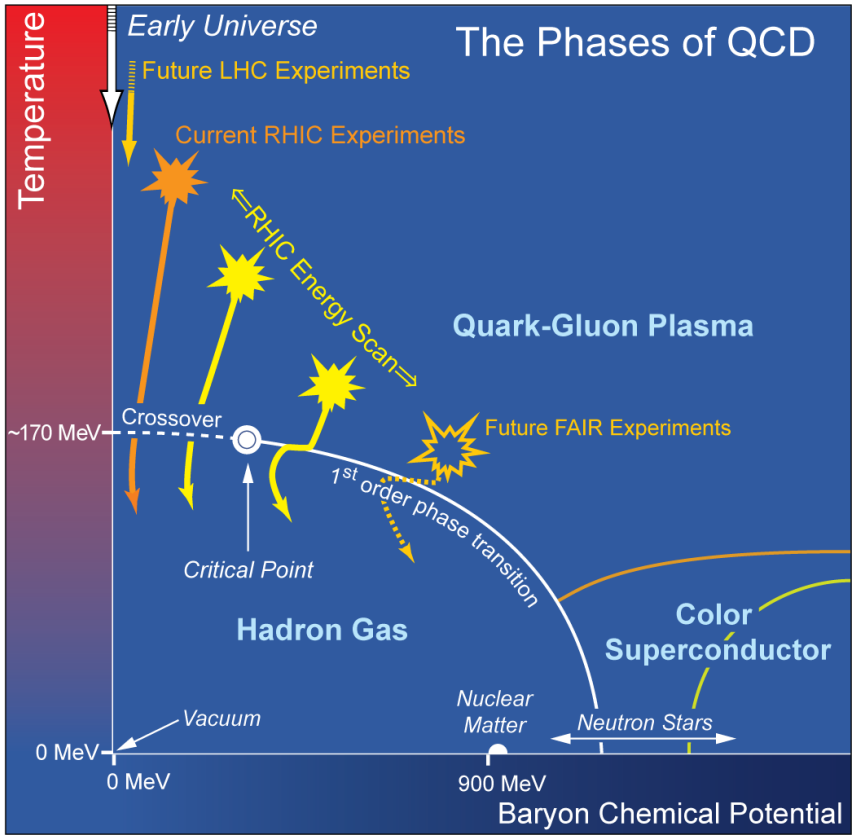
Partonic Collectivity at RHIC



Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): number of quarks ordering
s-quark hadron: smaller interaction strength in hadronic medium
light- and s-quark hadrons: similar v_2 pattern

=> Collectivity developed at partonic stage!

The QCD Critical Point



RHIC (200) & LHC: Determine the temperature T_{ini}, T_C

BES: Explore the QCD phase diagram determine T_E, location of the *phase boundary*

- Low baryon density, cross over

- LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram* at finite baryon chemical potential.

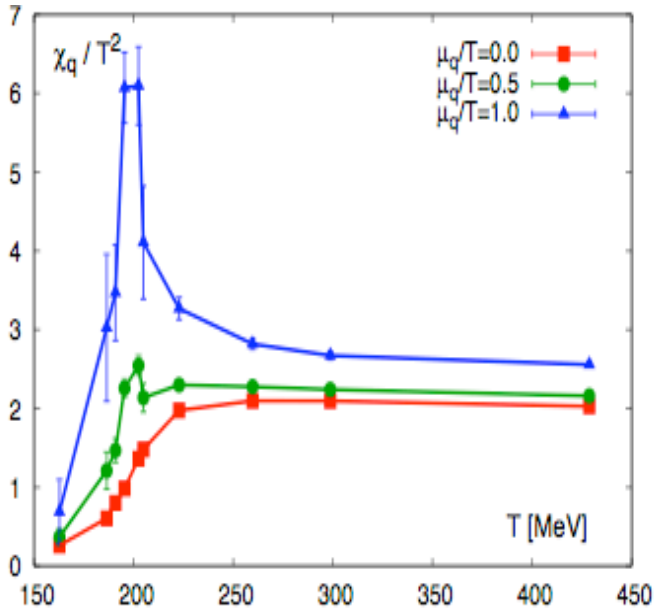
- Experimental evidence for either the critical point and/or 1st order transition is important for our knowledge of the QCD phase diagram*.

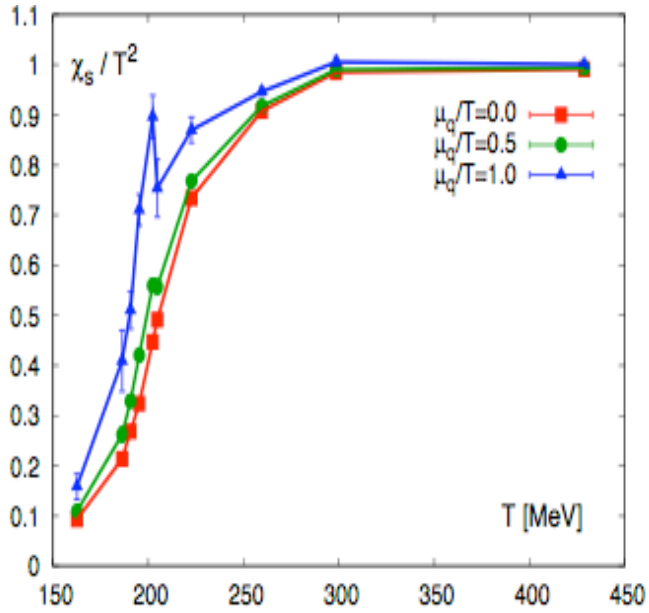
** Thermalization assumed*

*M. Stephanov, K. Rajagopal, and E. Shuryak, PRL **81**, 4816(98); K. Rajagopal, PR **D61**, 105017 (00)*

http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf

Observables: χ_q, χ_S





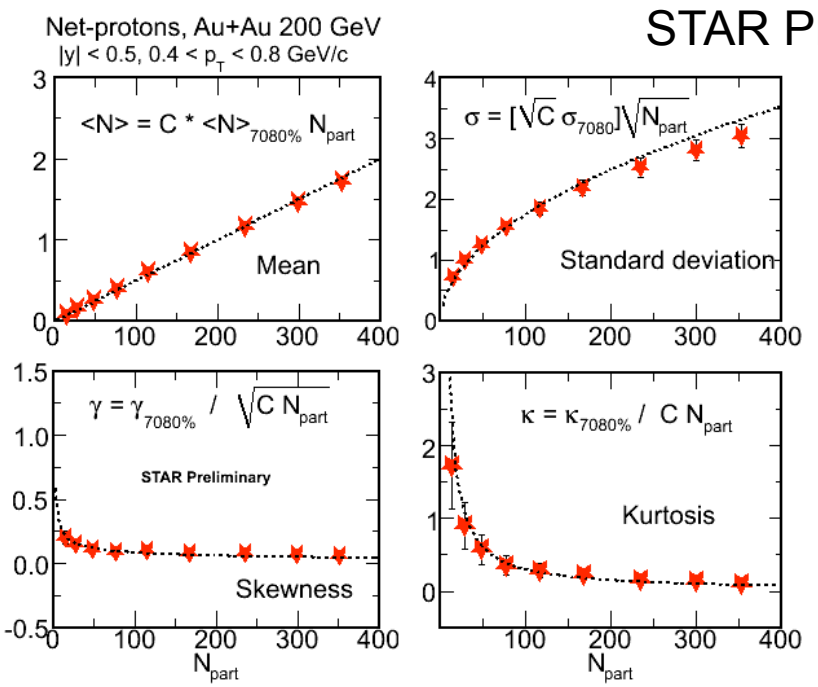
Event by event:

1. net-proton Kurtosis $K_p(E)$*
2. two proton correlation functions $C_2(E)$
3. ratio of the d/p
4. ratio of K/p

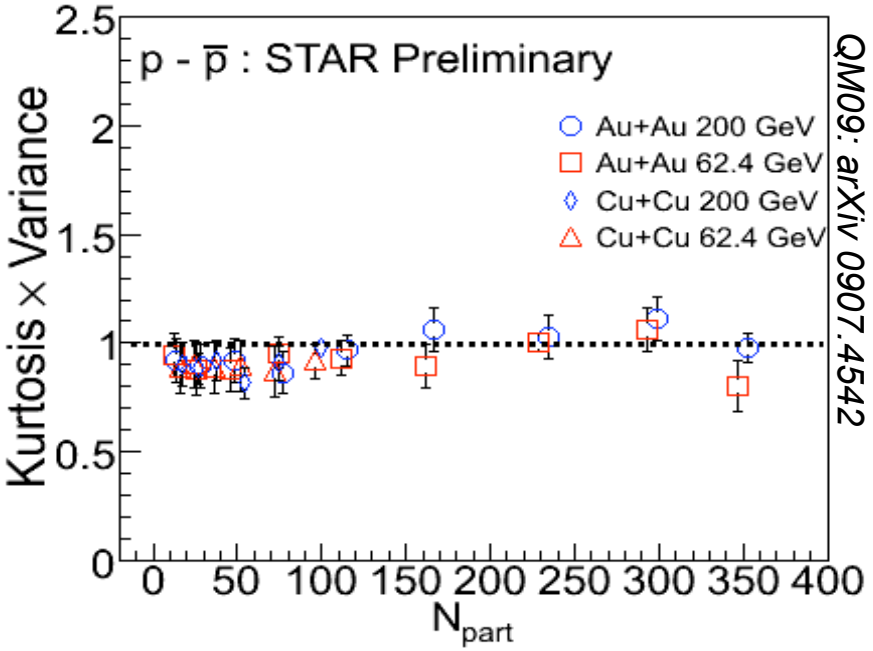
$$K_p = \frac{\langle N_p^4 \rangle - 3\langle N_p^2 \rangle^2}{\langle N_p^2 \rangle}$$

* *Gavai and Gupta, 03, 05; Gupta 0909.4630*
M. Cheng et al. 08
Gupta, Karsch, Stephanov, INT, 08

Higher Moments Analysis (BES)



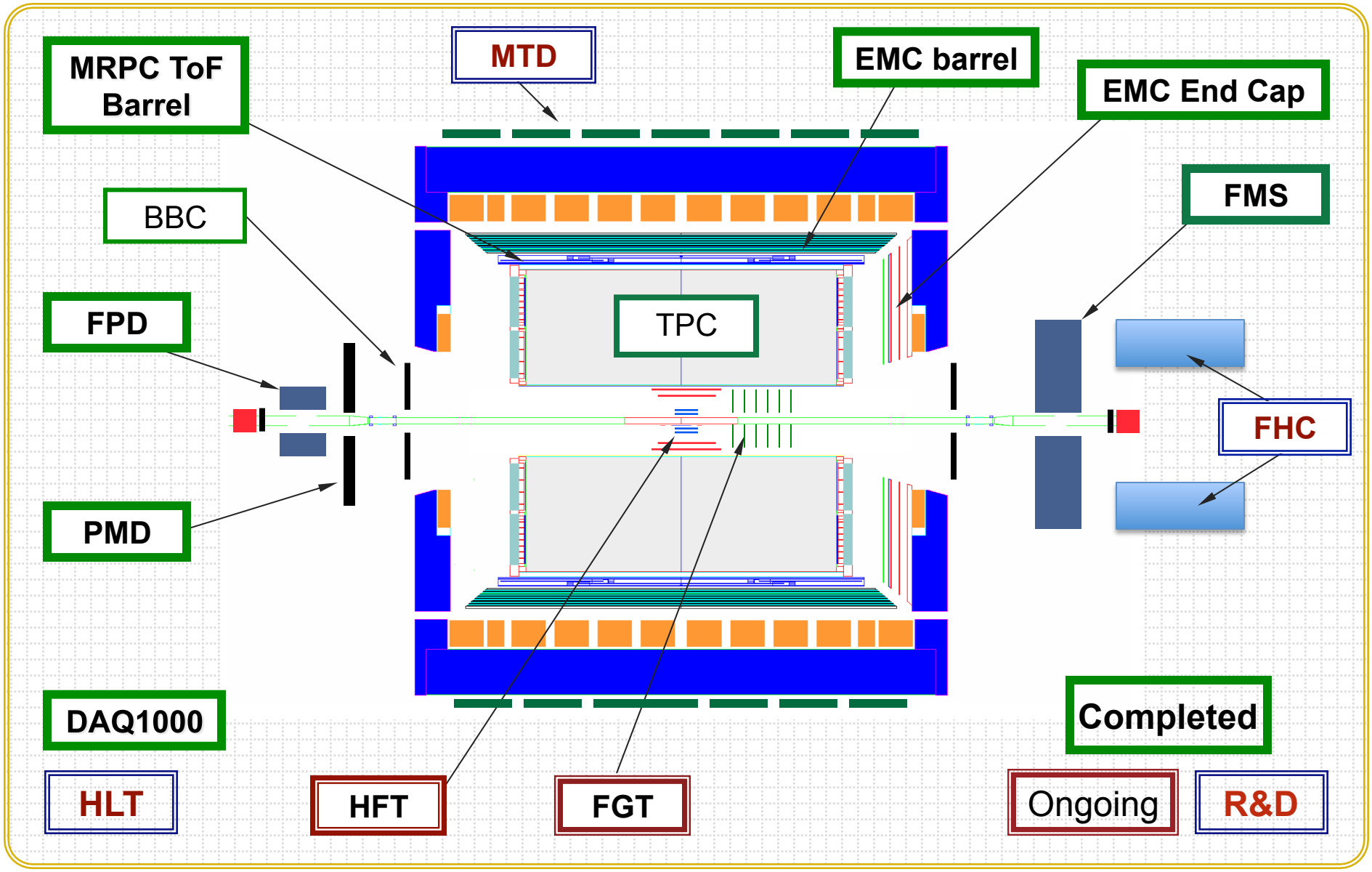
STAR Preliminary, QM09



1) Higher moments are more sensitive to QCD critical point related fluctuation.

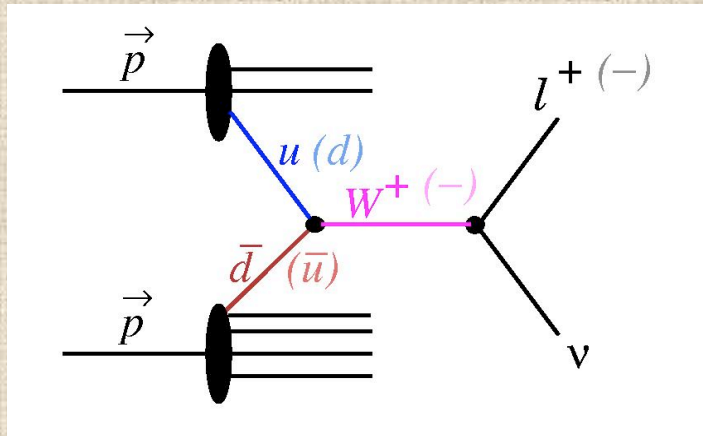
2) The 4th moment, Kurtosis, corresponding to the thermodynamic quantity: susceptibility of conserved quantum numbers. It is also related to the temperature of the system.

STAR Detector



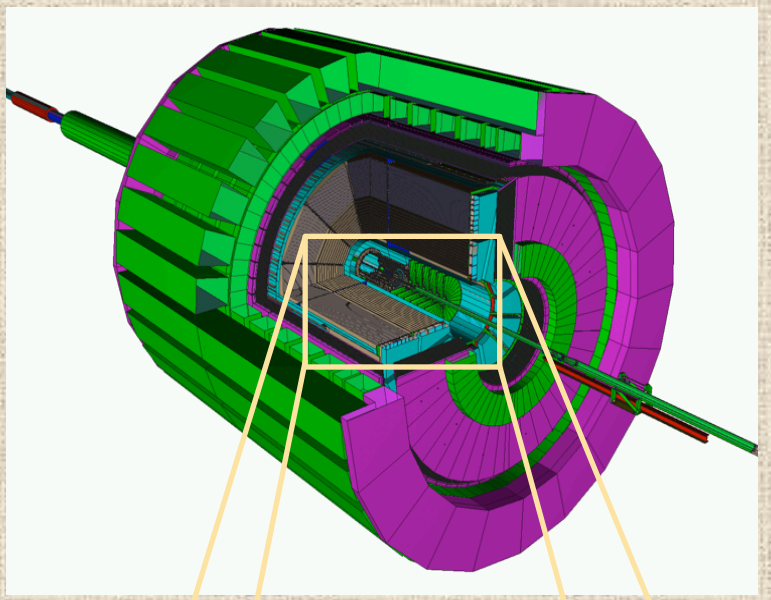
STAR: The *Sea-Quark* Program (2011)

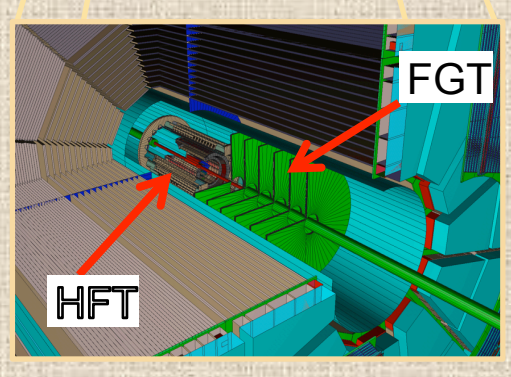
500 GeV p+p collisions



$$u + \bar{d} \rightarrow W^{+} \rightarrow e^{+} + \nu$$

$$\bar{u} + d \rightarrow W^{-} \rightarrow e^{-} + \bar{\nu}$$



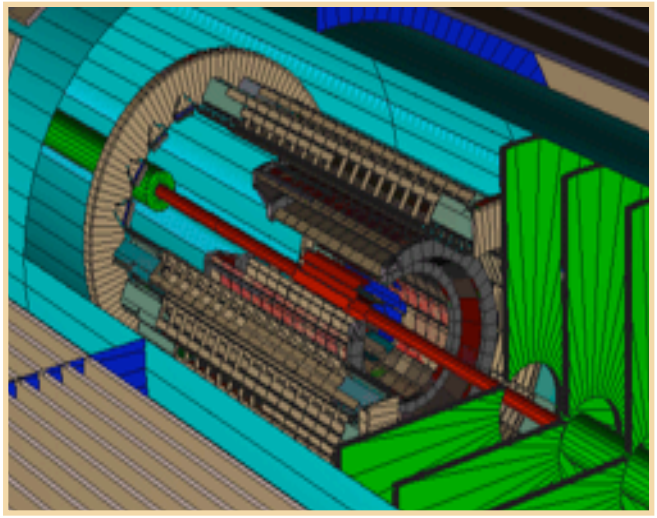


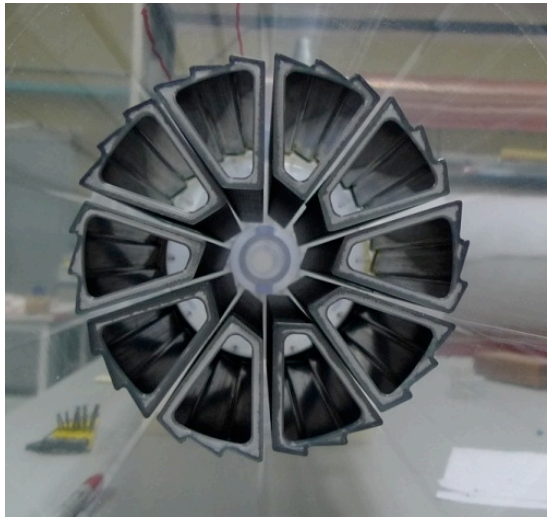
Forward GEM Tracker: FGT

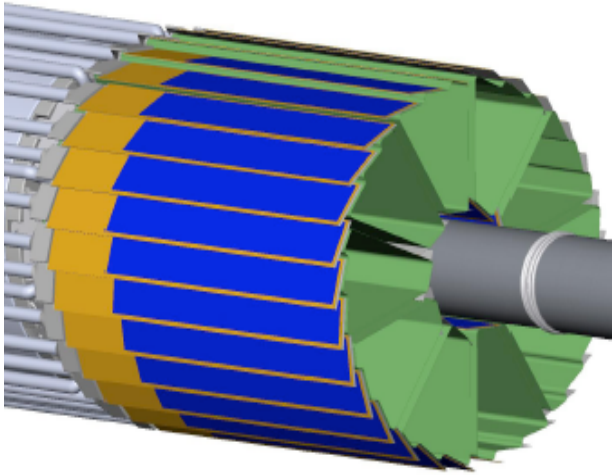
1) Charge sign identification for high momentum electrons from W± decay (Energy determined with EEMC)

2) Triple-GEM technology, Summer 2011 for Run12

STAR Heavy Flavor Tracker (2014)





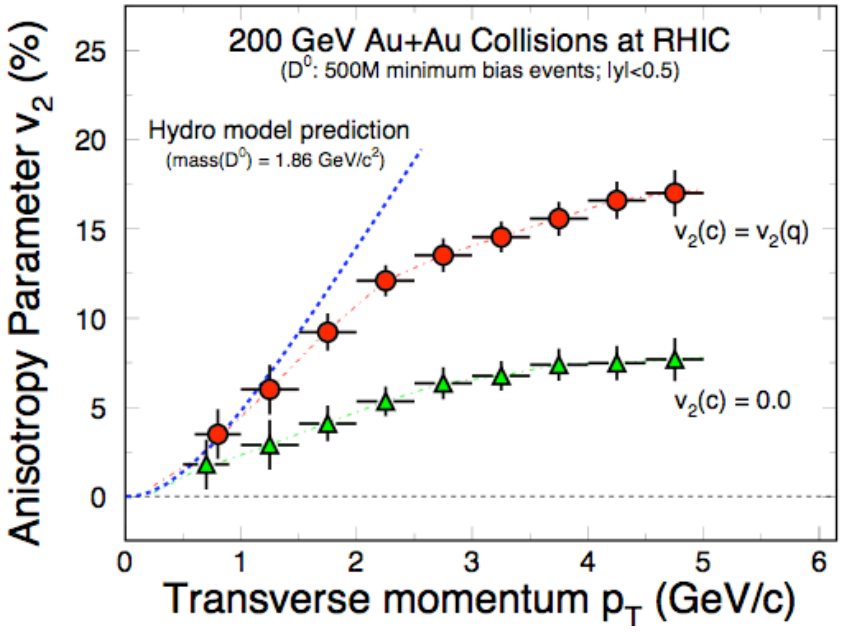


HFT: 2012-2014

1) Two-layer thin CMOS pixels; one-layer strips; SSD
2) First layer at 2.5 cm from beam pipe, 2π coverage
3) Resolution~20μm

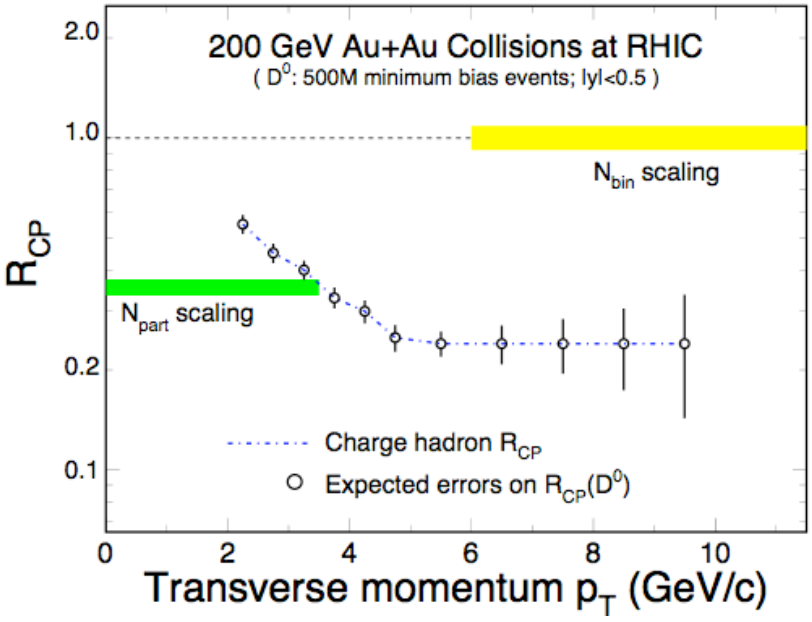
➔ **Measure open charm hadrons down to low p_T ~ 0.5 GeV/c**

HFT: Charm Hadron v_2 and R_{AA}



- 200 GeV Au+Au m.b. collisions (500M events).
- Charm hadron collectivity ⇨ drag/diffusion constants ⇨

Medium properties!



- 200 GeV Au+Au m.b. collisions (|y|<0.5 500M events)
- Charm hadron R_{AA} ⇨

- Energy loss mechanism!
- QCD in dense medium!

STAR QCD physics program for the next decade:

Spin Physics:

- 200 GeV: ***Δg*** inclusive and di-jets, γ-jet
- 500 GeV: ***sea quark*** helicity distributions
- 200/500 GeV: transverse spin phenomena

Heavy Ion Physics:

- Thermalization at 200 GeV
- QCD phase boundary and critical point (BES)
- In medium properties(?)

Low-x Physics:

- Study gluon-rich phenomena at RHIC
- Color glass condensate